Magic moments with John Bell

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John Bell, with whom I had a fruitful collaboration and warm friendship, is best known for his seminal work on the foundations of quantum physics, but he also made outstanding contributions to particle physics and accelerator physics.

John Stewart Bell and I met over tea in the common room of CERN's theory division. I had arrived a few weeks earlier, in April 1978, to work as an Austrian fellow. After one of the weekly theoretical seminars, the division held a welcome reception for all its newcomers. John was an impressive man, about 17 years older than me, with metal-rimmed glasses, red hair, and a beard. He asked about my research field, and when I replied, "quarkonium," he showed great interest. We immediately started a lively discussion in his office—the beginning of a fruitful collaboration and warm friendship.

The partner

Quarkonium, in analogy to positronium, designates a bound quark–antiquark system. Such states appear as narrow peaks in the energy spectra that are obtained after hadrons (particles containing quarks) interact; for that reason, quarkonium states are often called resonances. During the 1970s particle physicists discovered several such resonances, including the J/ψ, a bound state of charm and anticharm, and the Υ, a bound state of bottom and antibottom. The properties of those particles had to be understood, and so quarkonium states were a popular research field when John and I first got together.

At the time, physicists recognized that they could get pretty far considering just short-distance quark interactions. For instance, one could accurately predict the lifetimes of resonances.[1] John and I, however, wanted to understand the positions of the resonances; to do that, we had to include long-range interactions, which considerably upped the complexity of the calculations. For one thing, we had to consider interactions with and among gluons—particles analogous to photons—that convey the strong force that holds quarks together. That required us to go beyond perturbation theory and include the so-called gluon condensate: gluon fluctuations in the quantum chromodynamics vacuum.

Our approach was to approximate the full quantum field theory by something called potential theory, then a rather popular model. Within that framework, we succeeded in obtaining the ground-state energies of the J/ψ and Υ resonances[2] to within about 10%, though we were not able to construct a totally satisfactory bridge between the potential theory we used and the full-fledged quantum theory.[3] In car-

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rying out our work, we had to make use of mathematical functions called moments. In view of the surprising success we achieved in obtaining the ground-state energies, we titled our paper "Magic moments."

I well remember one of our afternoon rituals. John, a true Irishman, always had to drink tea at four o'clock; figure 1 shows us checking out a sample at his home. We also practiced our ritual in the CERN cafeteria, where John always ordered *deux infusions verveine, s'il vous plaît*—two infusions of verbena, his favorite tea, for us to enjoy together. There, in a relaxed atmosphere, we talked about physics and philosophy. At times we were joined by my artist wife, Renate, and then the three of us had heated debates about modern art.

The particle physicist

John was a highly esteemed particle physicist who fascinated me with his extraordinary personality. I felt his fatherly kindness and admired his knowledge and wisdom. He had a deep understanding of quantum field theory and liked to illustrate his ideas with basic examples. He wrote several celebrated papers in particle physics, of which I'll mention just a few.

John's PhD thesis, submitted in the mid 1950s, included a fundamental paper, "Time reversal in field theory."[4] In that work he proved the so-called *CPT* theorem, where *C* is the charge conjugation operator, which replaces particles with antiparticles; *P* is the parity operator, which performs an inversion through the origin; and *T* is the time-reversal operation. The theorem states that any quantum field theory satisfying a small set of standard assumptions must be *CPT* symmetric. (For the record, the assumptions are that the theory is Lorentz invariant, local, and possesses a Hermitian Hamiltonian.) For many years all the credit went to Gerhart Lüders and Wolfgang Pauli, who proved the theorem a little bit before John did, but nowadays John is also rightly recognized.

John's most far-reaching contribution to particle physics was a paper called "A PCAC puzzle: $\pi^0 \to \gamma\gamma$ in the σ-model," written with Roman Jackiw, who was a postdoc at CERN at the time.[5] The "PCAC" in the title stands for "partially conserved axial current." The details aren't important here, but the idea is that the existence of a symmetry—the chiral symmetry that seemed to imply a conserved axial current in the limit that pions are massless—precluded the decay of the pion into two photons. The solution to the puzzle was that the very process of quantization can lead to the breakdown of a classical symmetry; when that happens, the quantum theory is said to be anomalous. Ultimately, the chiral-symmetry anomaly is responsible for the pion decay.

Stephen Adler helped to clarify the anomaly issue in a paper written independently of Bell and Jackiw's work.[6] Nowadays, the chiral anomaly is often referred to as the Adler-Bell-Jackiw anomaly. Further studies revealed anomalies to be not just a pathology of the quantization procedure but also keys to a deeper understanding of quantum field theory.[7] Anomalies are widespread in physical theories, including the standard model of particle physics and theories of gravitation.

Figure 1. Afternoon tea was a must when John Bell (right) and I (left) were working together. This shot was taken at John's home in 1980. (Photograph © Renate Bertlmann.)

Also worthy of mention is John's influential review "Weak interaction of kaons," coauthored with experimentalist Jack Steinberger, and the pioneering work on vector bosons and neutrino reactions that John wrote with his colleague Martinus Veltman.[8]

The accelerator physicist

After graduating from Queen's University Belfast in 1949 with two bachelor's degrees, John began his scientific career at the UK Atomic Energy Research Establishment at Harwell. There he met his future wife, Mary Ross, a reactor and accelerator physicist. She was working in the theoretical physics division, which was led by Klaus Fuchs, the well-known physicist who later got sentenced to prison because of his atomic espionage for the Soviet Union. In 1954 John and Mary were married and began to pursue their careers together.

Shortly after John came to Harwell, he and Mary were sent to the Telecommunications Research Establishment in Malvern, where they stayed for about a year to work in William Walkinshaw's accelerator group. Walkinshaw highly appreciated John's abilities and noted that he "was a young man of high caliber who soon showed his independence on choice of project, with a special liking for particle dynamics. His mathematical talent was superb and elegant."[9]

Alone or in collaboration with Walkinshaw, John wrote several papers, mostly on how to focus a bunch of electrons or protons in a linear accelerator. In 1951 the whole accelerator group moved back to Harwell; soon after that, John turned to particle physics. By the end of the 1950s, he and Mary had become attracted to CERN, Europe's largest laboratory for basic science. The two moved there in 1960, John to be part of the theory division and Mary to join the accelerator research group.

During the 1980s John and Mary collaborated on accelerator work and wrote several papers together. One example is "Electron cooling in storage rings," in which they analyzed how changes in the electron velocity distribution would affect the electrons' ability to cool ion or proton beams in storage

Figure 2. My socks were always of two different colors, as John Bell observed in this cartoon accompanying his paper "Bertlmann's socks and the nature of reality."[8,10] The paper, which addressed the difference between quantum and classical correlations, was based on a colloquium, "Conceptual Implications of Quantum Mechanics," organized by the Hugot Foundation of the Collège de France.

rings such as the Low Energy Antiproton Ring at CERN.[8] That paper was dedicated to Yuri Orlov, an accelerator physicist who was then imprisoned in the Soviet Union for his human rights activism and was freed later on. Such an act of solidarity was typical of the Bells.

A particularly attractive work, in my opinion, was Bell's combination of the Unruh effect of quantum field theory with accelerator physics. According to William Unruh, an observer who is uniformly accelerated through the electromagnetic vacuum will experience blackbody radiation with a temperature proportional to the acceleration. John's idea was to use electrons as the accelerated observers and the polarization of the electron beam as the thermometer that measures the temperature of the blackbody radiation. The result, published together with Jon Leinaas, a CERN fellow from Norway, was that the effect of the acceleration was small but measurable.[8]

I become famous

At CERN, John was a kind of oracle for particle physics, consulted by many colleagues who wanted to get his approval for their ideas. Of course, I had heard that he was also a leading figure in quantum mechanics—specifically, in quantum foundations. But nobody, either at CERN or anywhere else, could actually explain his foundational work to me. The standard answer was, "He discovered some relation whose consequence was that quantum mechanics turned out all right. But we knew that anyway, so don't worry." And I didn't. John, for his part, never mentioned his quantum work to me during the early years of our collaboration.

At the end of the summer of 1980, I returned for a while to my home institute, the University of Vienna. There was no internet then, and it was a common practice for physicists to send preprints of their work to all the main physics institutions in the world before their papers were published. Each week we in Vienna would exhibit the new incoming preprints on a special shelf.

One day I was sitting in our computer room with my computer cards, when my colleague Gerhard Ecker rushed in, waving a preprint in his hands. He shouted, "Reinhold, look, now you're famous!" I could hardly believe my eyes as I read and reread the title of a paper by John, "Bertlmann's socks and the nature of reality."[8,10] I was totally stunned. As I read the first page, my heart stood still. The paper begins

> The philosopher in the street, who has not suffered a course in quantum mechanics, is quite unimpressed by Einstein-Podolsky-Rosen [EPR] correlations. He can point to many examples of similar correlations in everyday life. The case of Bertlmann's socks is often cited. Dr. Bertlmann likes to wear two socks of different colours. Which colour he will have on a given foot on a given day is quite unpredictable. But when you see that the first sock is pink you can be already sure that the second sock will not be pink. Observation of the first, and experience of Bertlmann, gives immediate information about the second. There is no accounting for tastes, but apart from that there is no mystery here. And is not the EPR business [regarding quantum correlations] just the same?

John's paper included a cartoon (figure 2) that showed me with my odd socks; seeing it nearly knocked me down. It came so unexpectedly. I had no idea that John had noticed my habit of wearing socks of different colors—a habit I had cultivated since my early student days as my special 1960s-era protest. The article immediately pushed me into the quantum debate, and it thus really changed my life.

Now the time had come to understand why the "EPR business" was not just the same as "Bertlmann's socks" and to appreciate John's profound insight. I dove into his seminal works on hidden-variable theory and on Bell's inequality (see section 3 of reference 8) and his foundational quantum works.[10] I was impressed by John's clarity and depth of thought. From then on we had fruitful discussions about foundational issues; those interactions were a great fortune and honor for me. A new world had opened up—the universe of John Bell—and it has fascinated me ever since.

The critic of von Neumann

John was never satisfied with interpretations of quantum mechanics. Even as a student at Queen's

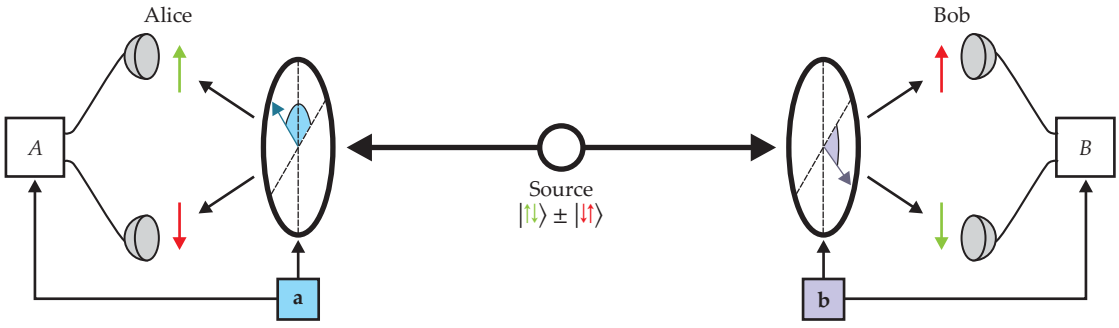

Figure 3. John Bell's famous inequality was derived for the setup illustrated here. A pair of spin-½ particles are prepared in a state of zero angular momentum, and each propagates freely in opposite directions to the measuring stations called Alice and Bob. Alice measures the spin in a direction **a** while Bob simultaneously measures in a direction **b**. In a hidden-variable theory, the measurement results are predetermined; the hidden variables might decree, for example, that if Alice measures her spin up, Bob will measure his down. (Adapted from R. A. Bertlmann, *J. Phys. A* **47**, 424007, 2014.)

University Belfast, he disliked the Copenhagen interpretation with its essential distinction between the quantum and classical worlds. He wondered where the quantum world stopped and the classical world began, and he wanted to get rid of the division.

When David Bohm published his reinterpretation of quantum theory as a deterministic, realistic theory with hidden variables,[11] his work was not appreciated by the physics community. Albert Einstein, for example, said that it "seems too cheap," and Wolfgang Pauli rejected it as "artificial metaphysics." John, however, was very much impressed and often remarked, "I saw the impossible thing done." For him, it was clear that in an appropriate reformulation of quantum theory, quantum particles would have definite properties governed by hidden variables. "Everything has definite properties," he would often say.

Hidden-variable theories take a set of observables $\{A, B, C, \ldots\}$ and assign to each individual system a set of eigenvalues $\{v(A, \lambda), v(B, \lambda), v(C, \lambda), \ldots\}$, one for each observable. Note that the assigned eigenvalues depend on the value of the hidden variable (or variables; there could be more than one) λ. For example, A, B, and C could be the x, y, and z components of an electron's spin in units of $\hbar/2$. Then, for a particular λ, $\{v(A), v(B), v(C)\}$ could be $\{+1, +1, -1\}$. Different members of an ensemble of states could have different assignments of the plus and minus signs according to their own individual λ; thus the hidden-variable theory must also provide a probability distribution for λ. When a quantum state—a state vector plus the specification of hidden variables—uniquely determines measurement outcomes, the state is said to be dispersion free.

In 1964 John started his investigation "On the problem of hidden variables in quantum mechanics"[10] by criticizing John von Neumann, who had given a proof that dispersion-free states, and thus hidden variables, are incompatible with quantum mechanics. What was the criticism? Consider three operators A, B, and C that satisfy $C = A + B$. If A and B commute, then the assigned eigenvalues must satisfy $v(C, \lambda) = v(A, \lambda) + v(B, \lambda)$.

Von Neumann, however, imposed the additivity property for noncommuting as well as commuting operators. "This is wrong," Bell grumbled, and before giving a general proof, he illustrated his dictum with the example of a spin measurement. Measuring the spin operator σ_x requires a suitably oriented Stern–Gerlach apparatus. The measurements of σ_y and $\sigma_x + \sigma_y$ require different orientations. Since the operators cannot be measured simultaneously, there is no necessity to impose additivity.

Thus John pointed to models for which results may depend on apparatus settings. Such models are called contextual, and they may agree with quantum mechanics. However, as demonstrated by the celebrated Kochen–Specker theorem, all noncontextual hidden-variable theories are indeed in conflict with quantum mechanics.[12]

The creator of Bell's theorem

At the end of his hidden-variable paper, John analyzed Bohm's reformulation more accurately. He discovered that according to Bohm's theory, in a system of two spin-½ particles—objects, like the electron, whose spin is $\hbar/2$—the behavior of one particle depends on the characteristics of the other, no matter how far apart the two particles are. He wondered, Was the dependence on remote characteristics just a defect of Bohm's particular hidden-variable model or would it hold more generally? Thus he was led to his seminal work "On the Einstein-Podolsky-Rosen paradox," which contained a proof that the result was general—the celebrated Bell inequality.[10]

John's profound discovery was that locality was incompatible with the statistical predictions of quantum mechanics. He proceeded from Bohm's spin version of the EPR paradox. As shown in figure 3, a pair of spin-½ particles in a spin singlet state (that is, the angular momentum of the pair is zero) propagates freely in opposite directions to measuring stations called Alice and Bob. Alice measures the spin in units of $\hbar/2$ along a direction **a** and obtains A; Bob measures along **b** and gets B. In a hidden-variable theory, the results are predetermined and specified by λ.

Assuming that A does not depend on Bob's

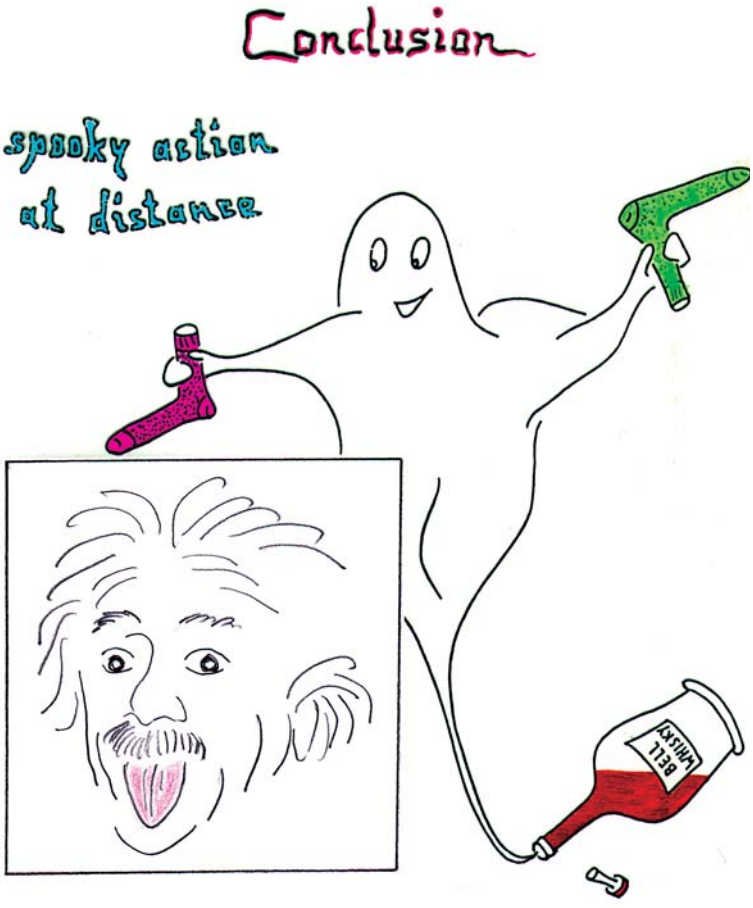

Figure 4. Real whisky bottles and spooky ghosts coexist in this cartoon that I drew to conclude a paper[17] dedicated to John Bell on the occasion of his 60th birthday.

measurement settings and B does not depend on Alice's—a condition now called Bell's locality hypothesis—the expectation value of the joint spin measurement of Alice and Bob is given by

$$E(\mathbf{a}, \mathbf{b}) = \int d\lambda\, \rho(\lambda)\, A(\mathbf{a}, \lambda) \cdot B(\mathbf{b}, \lambda).$$

Here the function $\rho(\lambda)$ represents a normalized distribution function for λ.

Alice's and Bob's spin measurements must satisfy $A(\mathbf{a}, \lambda) = \pm 1$ and $B(\mathbf{b}, \lambda) = \pm 1$. Given those relations, John was able to derive an inequality that must hold in *all* hidden-variable theories satisfying Bell's locality hypothesis: $1 + E(\mathbf{b}, \mathbf{c}) \geq |E(\mathbf{a}, \mathbf{b}) - E(\mathbf{a}, \mathbf{c})|$.

According to quantum mechanics, though, $E(\mathbf{a}, \mathbf{b}) = -\mathbf{a} \cdot \mathbf{b}$. Thus the quantum predictions violate Bell's inequality if, for example, **a**, **b**, and **c** lie in the same plane and are oriented, respectively, at 0°, 120°, and 60° relative to a common axis.

When I derived Bell's inequality for the first time, I was really impressed that it was possible to discriminate between all hidden-variable theories and quantum mechanics. How did John find his special combination of expectation values that contradicted quantum mechanics for certain sets of measurements? For me as a theorist the job was done. Nevertheless, experiment had to decide which was right, hidden-variable theory or quantum mechanics.

Classic experiments

The first to become interested in experimentally exploring Bell inequalities—nowadays there are several—was John Clauser in the late 1960s. At that time, working in the field was a courageous act. Clauser relates, for example, how he once had an appointment with Richard Feynman to discuss an experimental EPR configuration for testing the predictions of quantum mechanics. Feynman immediately threw him out of the office saying, "Well, when you have found an error in quantum-theory's experimental predictions, come back then, and we can discuss *your* problem with it."[13] Fortunately, Clauser remained stubborn and, with Stuart Freedman, carried out the experiment in 1972. The outcome is well known; the results were in accord with quantum theory and in clear violation of a Bell inequality. Later experiments, notably by Edward Fry and Randall Thompson, confirmed the result.[14]

The 1980s saw a second generation of Bell experiments carried out, in particular by Alain Aspect and his group.[15] Aspect and colleagues worked with polarized photons, and their goal was to incorporate a fast-switch mechanism for the polarizers to exclude a possible mutual influence between the two observers Alice and Bob. Again, a Bell inequality was significantly violated, and again, experimental results agreed with the quantum mechanics predictions. In my opinion, the Aspect work was a turning point; the physics community began to realize that such explorations were getting at something essential. Research started into what is nowadays called quantum information and quantum communication, a flourishing field.

The third generation of Bell experiments commenced in the 1990s and has extended into the 21st century. It has taken advantage of new technologies such as spontaneous parametric down conversion, which is an effective way to create entangled photons. Anton Zeilinger and his group, in a landmark experiment, were able to ensure that the directions in which photon polarization was measured were set randomly and independently.[16] Fascinating experiments on quantum teleportation, quantum cryptography, and long-distance quantum communication followed.

A great puzzle

The essential ingredient in all Bell inequalities is Bell's locality hypothesis. So far, all experiments looking for violations in Bell inequalities have found them, so we have to conclude, along with John, that nature contains a nonlocality in its structure. That nonlocality disturbed John deeply, since for him it was equivalent to a breaking of Lorentz invariance—a feature he could hardly accept. He often remarked, "It's a great puzzle to me. Behind the scenes something is going faster than the speed of light."

John was totally convinced that realism is the proper position for a scientist. That is, he believed that experimental results are predetermined and not induced by the measurement process. In his analy-

sis of EPR correlations, he did not so much assume reality as infer it. "It's a mystery," he said, "if looking at one sock makes the sock pink and the other one not-pink at the same time." He remained faithful to the hidden-variable program and was not discouraged by the outcome of the EPR–Bell experiments; rather, he found them puzzling. As he once remarked to me, "The situation is very intriguing that at the foundation of all that impressive success [of quantum mechanics] there are these great doubts."

At the end of his "Bertlmann's socks" paper, John again expressed his concern:

> It may be that we have to admit that causal influences *do* go faster than light. The role of Lorentz invariance in the completed theory would then be very problematic. An "ether" would be the cheapest solution. But the unobservability of this ether would be disturbing. So would the impossibility of "messages" faster than light.

I got back at John for "Bertlmann's socks" in a paper, "Bell's theorem and the nature of reality,"[17] that I dedicated to him in 1988 on the occasion of his 60th birthday. I sketched my conclusion in a cartoon, shown as figure 4. John, who strictly avoided alcohol, was very much amused by my illustration, since the spooky, nonlocal ghost emerged from a bottle of Bell's whisky, a brand that really did exist.

When I look back at my collaboration with John and remember his honest character and warm friendship, his deep and sharp intellect, and the knowledge I owe to him, I really feel privileged and thankful for the times I could spend with him. They were magic moments indeed.

I thank Renate Bertlmann for her company in all these years and for providing figure 1.

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